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Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Tsapekos, P., Kougias, P., & Angelidaki, I. (2015). *Mechanical Pretreatment to Increase the Bioenergy Yield for Full-scale Biogas Plants*. Abstract from 14th World Congress on Anaerobic Digestion, Viña del Mar, Chile.

Mechanical Pretreatment to Increase the Bioenergy Yield for Full-scale Biogas Plants

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Abstract
This study investigated the efficiency of commercially available harvesting machines for mechanical pretreatment of meadow grass, in order to enhance the energy yield per hectare. Excoriator was shown to be the most efficient mechanical pretreatment increasing the biogas yield of grass by 16% compared to the untreated one. The digestion of meadow grass as an alternative co-substrate had positive impact on the energy yield of full-scale biogas reactors operating with cattle manure, pig manure or mixture of both. A preliminary analysis showed that the addition of meadow grass in a manure based biogas reactor was possible with biomass share of 10%, leading to energy production of 280 GJ/day. The digestion of pretreated meadow grass as alternative co-substrate had clearly positive impact in all the examined scenarios, leading to increased biogas production in the range of 10%-20%.

Keywords
Anaerobic digestion; methane; meadow grass; mechanical pretreatment; energy production

INTRODUCTION

Biogas is promising renewable energy source and therefore, search for new biomasses appropriate for biogas is of high priority. Biogas can be produced by different substrates during anaerobic digestion (AD). The usage of energy-rich substrates is crucial for a sustainable biogas production. The digestion of livestock manure for biogas production is widely used in Denmark (Raven and Gregersen, 2007). However, due to the low methane potential of manure the mono-digestion system is not economically viable (Gerin et al., 2008). Since in Denmark the permanent grassland and meadows cover an area of 229 thousand hectares (EUROSTAT, 2008), meadow grass can be examined as an alternative co-substrate due to their higher methane yield compared to livestock manure.

Meadow grass was identified in the past for bioenergy production reaching remarkable results with highest methane yield of 406 ml CH_4/gVS (Raju et al., 2011). Nevertheless, lignocellulosic biomass is rather recalcitrant and in order to improve the access of microorganisms to the degradable organic fraction, an efficient pretreatment method is needed. Mechanical pretreatment methods are widely known for increasing the methane yields of lignocellulosic substrates (Kratky and Jirout, 2011). The effective application of mechanical pretreatment can improve the gross energy yield for an economical and feasible process.

Considering these issues, the aim of this work was to elucidate the effect of commercially available shredding machines on energy yield enhancement. Moreover, a preliminary study was taken place to evaluate the surplus energy that can be produced by the co-digestion of mechanically pretreated meadow grass with livestock manures.

MATERIALS AND METHODS

Meadow grass characteristics and mechanical pretreatment methods

Separate areas from four fields in Lintrup, Denmark, were harvested with three commercial shredding machines. The fields had the same climate conditions and were harvested during the same period. The machines used to mechanically pretreat the meadow grass were; a) a chopper, consisted of a rotor with multiple sets of attached hammers which cut the grass to approximately 5cm length and b) an excoriator, consisted of multiple coarse blades placed in parallel, which cut most of the grass to less than 20cm length and also disrupted the plant tissue. As control, a disc mower, which is the common practice for grass harvesting, was used (untreated grass). The disc mower only cut the grass from the field (grass length more than 20cm) and did not damage the grass surface. The commercial shredding machines had the same energy requirements and needed equal time to harvest the field, as their dimensions and driving speed on the field were the same

Biochemical methane potential (BMP) assays

BMP assays were conducted according to the standard protocol described by Angelidaki et al. (2009). Batch reactors operated under thermophilic conditions (54 ± 1°C) had a total volume of 547 ml and working volume of 200 ml. The initial organic load of the meadow grass was 2 g VS/L. After harvest, the collected meadow grass was stored at -18 °C until usage.

Analytical methods

Total solids (TS) and volatile solids (VS) were analyzed according to the methodology described by APHA standard methods for the examination of water and wastewater (2005). The methane yield was analyzed using a gas-chromatograph (Shimadzu GC-8A, Tokyo-Japan), as described by Kougias et al., (2014).

RESULTS AND DISCUSSION

Mechanical pretreatment effect on energy yield per hectare

The average methane yields of meadow grass pretreated with the different machines are presented in Table 1. It was found that the most efficient mechanical pretreatment method was the excoriator, resulting in 16% and 6% higher methane production compared to the corresponding one of the disc mower and chopper, respectively. The increase in the methane productivity is in accordance with a previous study, which reported that mechanical pretreatments could enhance the methane production of ensiled meadow grass by 8%-25% (Tsapekos et al., 2014). The energy yields per hectare, which can be obtained from the total harvested area, are based on the crop yield and are calculated for the complete crop rotation as average per annum. It was estimated that the average crop yield in the four fields was 5.7 ton DM/ha and therefore the average biogas yield of meadow grass pretreated by the excoriator was 1705 m^3/ha. This machine reached the highest methane productivity, corresponding to approximately 254 million m^3 CH_4/year or 218 thousand tons crude oil equivalents (COE)/year (Table 1). The second most efficient harvesting machine (chopper) would reach a methane productivity of 242 million m^3 CH_4/year or 208 thousand tons COE/year.

Table 1. Biogas yield from meadow grass

Parameters	Disc mower	Chopper	Excoriator
TS (%)	60.0 ± 2.41	66.2 ± 3.12	63.9±1.37
VS (%TS)	91.71 ± 0.26	91.29 ± 1.77	92.85±3.06
Methane yield (m^3/kgVS)	0.292 ± 0.03	0.324 ± 0.03	0.346±0.04
Energy in biogas (MJ/ton/year)	6070 ± 517	7370 ± 858	7742±749
Biogas yield (m^3/ha/year)	1338 ± 146	1623 ± 191	1705±196
Gross energy yield (GJ/ha/year)	33 ± 4	40 ± 5	42±5
Methane productivity (million m^3/year) *	199 ± 24	242 ± 22	254 ± 29
COE (thousands tons/year) *	171 ± 20	208 ± 25	218 ± 25

Values are the average obtained by the four fields, symbol ± designates standard deviation

* 1 m^3 CH_4 = 10 kWh, 1 kg COE = 11.63 kWh (Amon et al., 2007).

Case study scenarios on energy yield of full-scale biogas plants

According to the results from the batch assays the excoriator was the most efficient pretreatment method; thus we further investigated the effect of this pretreatment method on a case study in full-scale application. The exploitation of pretreated meadow grass as additional substrate in full-scale biogas plants treating manure was examined under three different scenarios; co-digestion with cattle manure (Scenario 1), co-digestion with pig manure (Scenario 2) and co-digestion with a mixture of cattle and pig manure (Scenario 3). In all scenarios, the energy output from co-digestion of manure together with pretreated grass was evaluated and compared with the corresponding one using untreated meadow grass.

In the case study, a thermophilic full-scale biogas reactor with working volume 3000 m^3 and hydraulic retention time (HRT) of 15 days was considered. It was also assumed that a typical combined heat power (CHP) system converts the produced biogas to approx. 40% electricity and 45%-50% heat, the rest is losses (10-15%). Finally, based on preliminary results, the methane potential of cattle and pig manure was found to be 399 ml CH_4/gVS and 214 ml CH_4/gVS, respectively (Kougias et al., 2010, 2014).

In all scenarios the process could be accomplished till a grass share of 10% in terms of VS in the influent feedstock. A further increase of grass load in the feed will increase the TS content more than 11%, resulting in operational problems (e.g. clogging, collapse of mixing system) and significant organic overload. In scenario1, the maximum obtained energy was calculated to be 280 GJ/day. The co-digestion of pretreated meadow grass using the excoriator led to 14% higher energy output compared to the co-digestion with untreated grass (241 GJ/day). Moreover, it was found that the produced biogas could generate 60 MWh/day heat and 48 MWh/day electricity. In scenario 2, the impact of the pretreatment on the methane productivity was higher compared to scenario 1. It was shown that the excoriator pretreatment improved the energy yield by 20%, compared to the untreated grass. Additionally, the energy yields obtained from the co-digestion of pig manure and meadow grass were significantly increased due to the addition of grass in the feedstock. This could be explained by the fact that meadow grass has higher methane potential compared to pig manure and also because pig manure has high ammonia content and thus the co-digestion with meadow grass lead to a more balanced C/N ratio improving the AD process. The maximum biogas production was calculated to be 4968 m^3/day (i.e. 42 MWh/day heat and 34 MWh/day electricity). Similarly, in scenario 3, in which mixture of cattle and pig manure was used, the maximum energy output using pretreated grass was 234 GJ/day, which was 17% higher compared to the co-digestion with the untreated one. The produced biogas could generate 50 MWh/day heat and 40 MWh/day electricity.

Table 2. Increase of biogas production due to co-digestion of meadow grass with manure

VS CONTENT (%)		Cattle manure			Pig manure			Manure mixture (1:1)		
Grass	Manure	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
0	100	3192	127		899	36		1900	76	
5	95	5112	203	10%	2934	117	17%	3885	155	13%
10	90	7032	280	14%	4968	198	20%	5869	234	17%

(1) CH_4 production, m^3/day (2) Energy production, GJ/day (3) Difference (%)

CONCLUSIONS

Mechanical pretreatment can significantly enhance the methane production of meadow grass. It was found that the utilization of a commercial excoriator resulted in 16% higher methane yield compared to untreated grass. Additionally, case study showed that the exploitation of permanent grasslands as alternative co-substrate in full-scale biogas plants treating manure could boost the energy production and result in sustainable biogas production. More specifically, the addition of pretreated grass in the feedstock of a biogas reactor could increase the energy production by 10%-20% compared to the processes, in which untreated meadow grass was used as a co-substrate.

ACKNOWLEDGEMENTS

The authors would like to acknowledge financial support by the Danish Agency of Energy program under EUDP "New technology for an efficient utilization of meadow grass in biogas reactor" and Hector Garcia for technical assistance.

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